

Soundscape Reproduction and Synthesis

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Abstract

The aims of this work were to investigate (i) whether soundscape perceptual dimensions are correctly reproduced by ambisonic loudspeaker playback, (ii) whether soundscape dimensional analysis is robust to changes of location and from the field to laboratory playback, and (iii) whether a simple soundscape synthesis can be used to interactively design a soundscape. The first two aims were addressed by an experiment which attempted to repeat the dimensional analysis made by Kang (Kang, J. (2007), *Urban Sound Environment*. London: Taylor and Francis). Kang used semantic differential scales to conduct an in-situ survey of two urban soundscapes in Sheffield, UK. He used factor analysis to derive four perceptual dimensions from the responses. The present work repeated this approach, but the fifteen participants were judging ambisonic recordings of four soundscapes in Manchester, UK. The present work found very similar dimensions to Kang but with more variance explained: relaxation/calmness (41%), dynamics/vibrancy (10%), communication (7%) and spatiality (7%). The dimensions from the two studies load onto the semantic scales in a similar way. These results indicate that an ambisonic reproduction of a soundscape gives

similar results to field experiments, though with more variance explained. They also show that dimensional analysis of soundscape response is robust enough to produce similar results for different locations in different cities.

To investigate the third aim, the ambisonic reproduction was extended to a system which allowed independent interactive control of sixteen foreground sounds set in an ambisonic background soundscape. Eight participants were able to use this system to successfully design a soundscape that expressed their intentions. It was found that the designed soundscapes seemed to be based more on participant expectation of typical urban soundscapes than on their preference for individual sounds. These results suggest that a more sophisticated soundscape synthesiser might be suitable for real design problems.

1. Introduction

Several important aspects of soundscape perception and cognition have been described in the literature. The major elements discovered to date are: soundscape dimensions [1-4]; sound and soundscape categories [5, 6]; soundscape components [7], semantic meaning of soundscapes [8] and soundscape expectation [9]. Most of these results have been produced from fieldwork: the researcher asks the listener(s) some questions while they are in a real soundscape, or immediately afterwards. A few studies (for example [4]) have used laboratory reproduction: recordings are made of a soundscape and later reproduced to listeners. The merits of fieldwork and laboratory tests contrast: fieldwork seems to offer realism, in that listeners are exposed to a real soundscape in a real environment and all the sensory stimuli are thus authentic. Laboratory tests offer control, not least in that each listener can be exposed to exactly the same sound stimulus. Scientific research usually prefers closely controlled experimental conditions, so the preponderance of fieldwork studies in the literature suggests that researchers question whether soundscapes can be adequately reproduced in the

laboratory. This question was directly addressed by Guastavino et al. [10] who showed that a first-order ambisonic loudspeaker system successfully reproduced soundscapes, in the sense that semantic aspects of user experience were similar in the original soundscape and its reproduction. Guastavino et al. introduced the term ecological validity to soundscape research and used it as a way of exploring how well soundscape reproduction works. They explained that an ecologically valid laboratory experiment is one in which participants respond in the same way as they would under ecological conditions. Guastavino et al. measured the similarity of participants' linguistic responses between field and laboratory reproduction and used this as a measure of ecological validity. This revealed that the ecological validity of different soundscape reproductions was found to vary somewhat with the type and content of the soundscape. Despite this result, reproduction has not been widely used in soundscape research since, and most work continues to rely on field experiments. This might be because ecological validity of soundscape reproduction would depend on the successful reproduction of all the aspects of soundscape perception and cognition of interest to a researcher, and not just those studied by Guastavino et al. Guastavino et al. focussed on the reproduction of semantic and cognitive aspects of soundscapes, including semantic categories and realism. The first aim of the work reported in this paper is to test the reproduction of a different feature of soundscape perception, namely whether the perceptual dimensions of soundscapes are correctly reproduced in laboratory listening tests.

Decomposing soundscape perception into its constituent dimensions is an attractive analysis technique because it holds the possibility that soundscapes could be classified by their position in the dimensional space, that changes in the soundscape could be measured by changes in this position, and that the psychological dimensions might even be related to physical metrics and thus predicted by them [1]. Dimensional analysis of outdoor soundscapes has been attempted by a small number of research groups. Kang [2] used

eighteen semantic differential scales with 223 subjects in two urban squares. He extracted four principal factors. All the factors have significant relationships with many of the eighteen scales, so attempting to summarise the factors in one word leads to some generalisation. Nevertheless, Kang's perceptual factors can be described as: relaxation, communication, spatiality and dynamics. Three other soundscape dimensional results exist in the literature [1, 3, 4]. These research groups found similar but not identical dimensions to Kang (their results are discussed in more detail later in this paper). This raises the question of how robust a dimensional model of soundscape perception is. Are the dimensions specific to a location, or a country, or do they depend on the scales used in the data collection? Does it matter if the soundscapes were experienced in situ (Kang) or if they were reproduced by an audio system in a laboratory (Cain et al.)?

If soundscapes can be successfully reproduced by a spatial audio system, then this may open up possibilities of mixing a soundscape and even simulating a soundscape. These techniques might be useful both for researching soundscape preference and ultimately for soundscape design. There is considerable interest in using soundscape concepts to actively design the acoustic environment of a location. Brown and Muhar [11] suggested a way of deriving acoustic criteria and using them for soundscape design. Zhang and Kang [12] used an analysis of the important aspects of existing soundscapes to make suggestions for how soundscapes could be deliberately designed. Davies et al. [13] described a simple tool for evaluating existing soundscapes and suggested how it could be used to support design decisions to intervene in or change a soundscape. Compared to visual design, however, there is a striking lack of creative tools for soundscape designers. There is no equivalent of the architect's sketch pad for soundscape design. A valid soundscape synthesis where the user can interact with and change the soundscape might offer a way towards a useful creative design tool.

This paper reports the results of two experiments. The first experiment directly addresses the questions of whether a spatial audio system can correctly reproduce soundscape dimensions and how reproducible those dimensions are between locations, listeners and experimenters. The second experiment employs a method for synthesising a soundscape and examines whether it can be used to interactively design a soundscape.

2. Experiment 1: Soundscape reproduction

2.1 Method

The first experiment sought to reproduce the soundscape dimensions found by Kang in the field, but in a different city, some years later, using a spatial audio system rather than in-situ exposure. Recordings were made of the soundscape in four urban locations in Manchester city centre (in the UK). A soundfield microphone was used to make first-order ambisonic recordings. Two of the locations were at opposite ends of St Ann's Square, a pedestrianised shopping area bounded on one side by a cobbled road. The first recording (A) was near the cobbled road, and the second (B) was near a busking musician. (St Ann's Square was much studied by the Positive Soundscape Project [7].) The third location was a pedestrianised underpass, and the fourth was on a busy road with a railway bridge going over it. Figure 1 shows snapshots of the four locations. The recordings were reproduced using an eight-loudspeaker three-dimensional first-order ambisonic system in a semi-anechoic chamber at Salford University. Sound levels at the listener's position were the same as at the point of recording (L_{Aeq}). One 30-second recording was used for each of the four locations. Fifteen participants, all students or lecturers in acoustics, completed the experiment. The participants were allowed to replay each recording as many times as they wished. No visual stimulus was supplied.

Kang used 11-point two-sided semantic differential scales to collect responses to the soundscapes in his field study. We followed this method with the nineteen response scales shown in Table 1. Some alterations were made to Kang's scales to better fit this experiment. A scale of calming-agitating was added because results from the Positive Soundscape Project had shown that calmness plays a significant role in soundscape evaluation [4]. Kang's finding that communication was a significant factor resulted in the addition of the communal-private scale. Kang's scale of echoed-deadly was deemed confusing, and altered to reverberant-anechoic. Far-close was also changed to far-near as the word near does not possess the dual meaning that close does. Lastly, the scale of directional-everywhere was replaced with directional-universal.

2.2 Results and Discussion

The completed experiment resulted in nineteen scale values for each of four soundscapes, for each of fifteen participants. Figure 2 shows the scale values averaged across participant for each soundscape. As expected, the soundscapes produce different ratings on most scales. For example, it is not surprising to find that St Ann's Square (B) is more comfortable than the busy road. More interestingly, there seem to be two pairs of soundscapes: The pedestrian underpass and St Ann's Square (B) in Fig. 2 (b) have similar values on several scales and are more liked than the busy road and St Ann's Square (A) in Fig. 2 (a). This might be explained by the presence of foreground traffic sounds in the latter two soundscapes. It is worth noting that caution must be exercised in using the mean values of scale responses to evaluate a soundscape. In a study of urban soundscapes, Raimbault [14] found that some semantic scales produced responses which were not normally distributed, as participants sometimes formed two different groups with their responses. No evidence was found in the present data that participants did not use the scales in the same way, and it is

important for the purposes of comparison with Kang's earlier experiment that the same method is followed here.

The software package SPSS was used to conduct a principal component analysis (PCA) on this data. The analysis was first partitioned into the four soundscapes, and then combined for an overall view. For the partitioned PCA, similar results were found for each soundscape. For each location, four components explain 71 to 74% of the variance in the scale values. Figure 3 illustrates the relationship between the input semantic scales and the first three output components for each of the four soundscapes. For all the locations apart from St Ann's Square (A), the first component loads highly onto the scales Comfort, Quiet, Pleasant, Like, Gentle and Calming. Component one thus seems to be a consensus judgement on pleasantness. Component 2 seems to be assessing the dynamics of the soundscapes, because for the same three locations it is associated with the scales Fast and Varied. Component three seems to be assessing the meaning of the soundscape because it is associated with the scales Social, Communal and Natural.

The broad similarities between the component spaces in Fig. 3 suggest that the soundscapes are being judged by the participants with the same perceptual framework. The whole set of data was therefore combined for one overall PCA across the four soundscapes. This resulted in four dimensions that explain 65% of the variance in the scale values. The dimensions load onto the scales with the factors shown in Table 2 and Figure 4 shows the scales plotted as vectors in the first three dimensions. Combining the soundscapes tends to produce a clearer picture of the dimensions in Fig. 4. The first dimension is strongly associated with Like, Pleasant, Comfort, Gentle, Quiet, Calming and Smooth. It could tentatively be called Relaxation/Calmness. The second dimension is associated with Varied, Meaningful, Fast and Sharp. It could be called Dynamics/Vibrancy. The third dimension is most strongly associated with Social and Communal – it could be called Communication. The

final dimension is associated with Directional and Far, so it could be named Spatiality. These loadings are not identical to those found by Kang [2] but they are similar. Kang found dimensions of relaxation (26% of variance explained), communication (12%), spatiality (8%) and dynamics (7%). The main difference between our results and Kang's is the increased variance explained by the first factor. The most likely explanation for this is that the controlled laboratory conditions, especially the exposure of participants to identical stimuli, have reduced the influence of extraneous factors. In our experiments, the four soundscapes produced similar but not identical dimensions when analysed individually. This effect is perhaps due to a different mix of sound sources in each soundscape and this probably accounts for some of the small remaining differences between our results and Kang's.

The dimensions found in three other studies in the literature are not much more different. In a large project, Axelsson et al. used 116 semantic scales to characterise the response of 100 listeners to fifty soundscapes [1]. They produced a three-dimensional space with factors pleasantness (50%), eventfulness (18%) and familiarity (6%). Guillén and López Barrio [3] reported three dimensions, named emotional evaluation and strength (42%), activity (14%), and clarity (10%). Finally, Cain et al. found two principal dimensions: calmness (60%) and vibrancy (20%); with visual stimulus having little effect on the dimensions in this binaural reproduction [4]. The first dimension in all the studies seems to be very similar: calmness/pleasantness. All the studies except Kang's have the same second dimension: activity/eventfulness. (Kang also has this dimension, but places 'dynamics' as dimension 4.)

The effect of the ambisonic reproduction in this experiment can be compared to results reported by Guastavino et al. [10]. They exposed participants to soundscapes in situ and via an ambisonic reproduction. A linguistic analysis of the subsequent interviews found that the reproduced soundscape produced similar semantic categories to the in-situ

soundscape. The present results add to the confidence we can have in ambisonic reproduction by showing that the reproduction also seems to be faithful for the perceptual dimensions.

It is interesting that some of the dimensional studies discussed above included visual stimulus (e.g. Kang) and some did not (e.g. Cain et al.). The broad agreement of the findings between the various studies suggests that visual stimulus is not very important in determining the auditory dimensions, as suggested by Cain et al. However, there is also evidence in the literature that seems to contradict this. For example, Viollon et al. [15] found that visual scenes influenced judgements of soundscape pleasantness and relaxation. One possible way of resolving this disagreement might be to consider the role of attention. It has been previously reported that the attention mechanism has a significant role to play in soundscape perception [16]. Top-down attention can be focused on different sensory attributes at a range of different scales: on the overall impression of a place (sights, sounds, smells), on the soundscape, or on a particular sound or sound source. In one kind of study, participants might be asked to assess their impression of a place using both audible and visual stimuli. Attention is drawn to both sensory modes and a visual stimulus could influence the rating of an auditory stimulus. In another kind of study participants might be asked only to listen to the soundscape and evaluate that. Determining their attentional set in this way might then reduce the importance of other senses.

3. Experiment 2: Soundscape Synthesis

3.1 Method

Experiment 1 has shown that ambisonic reproduction works well enough to produce expected responses in listeners for a real soundscape. This form of reproduction represents the sound field as spatial components and so it is a small step to ask if it could be adapted so that individual components of the soundscape could be manipulated in a meaningful way – can one ‘mix’ a soundscape? The approach adopted here was to construct a simple synthesis

of a soundscape by combining recordings of ‘real’ sounds made in the field. The method for the soundscape synthesis is described in detail elsewhere [17] and summarised briefly here. Separate recordings were made of the background ambient soundscape (with a four-channel soundfield microphone) and individual foreground sources, such as footsteps (with a close mono microphone). For playback, an eight-loudspeaker first-order ambisonic system was used, in a semi-anechoic chamber. The foreground sounds are each looped as appropriate, mapped to a specific location and layered over the background track. It is important to note that the foreground sources are not limited to the loudspeaker positions but can appear at any point around the listener. This arrangement allowed for the amplitude and position of each sound source to be controlled independently. Additional processing, such as reflection and reverberation could also be applied to each source independently. These parameters could all be varied in real time during playback, allowing direct interaction with the synthesised soundscape. A small mixing desk was used as the user interface. As the participant changed the position of each control on the mixing desk, the value of this parameter was continuously recorded, allowing us to build up a picture of how participants interacted with the synthesised soundscape.

In the experiment reported here, there were eight participants, aged 20-37, and all were naïve listeners. The recordings were made in St Ann’s Square in Manchester. Sixteen foreground sounds were recorded and these are briefly described in Table 3. The participants were told to imagine they were in an urban location. The task for the participants was to synthesise what they considered to be the most appropriate soundscape for St Ann’s Square. Participants were provided with a verbal description of the square. One soundscape was synthesised by each participant. Each sound source could be listened to in context with the background ambient track or on its own. In pilot experiments [17] it was found that allowing the participants a period of time to ‘play’ with the simulator provided the most engaging

experience for them, they were able to familiarise themselves with the simulator control and operation, as well as try their own ideas out in soundscape design. Throughout the experiment, the ambient track was looped over a two minute period and was the background upon which foreground sounds were added. Once the experiment began, the participants were first asked which of the sixteen sound sources they wanted to keep. They were also asked if they would expect to hear this sound in St Ann's Square. Participants were then asked to rate the pleasantness of each sound in context using a semantic differential scale (pleasant – unpleasant). Once the source sounds had been selected the participant was asked to adjust the level of each sound source in relation to the ambient track and to a level which they thought was acceptable. The participant was also asked to adjust the overall level of the ambient track using the controller. Participants were informed at the beginning of the experiment how to adjust the sound levels. The material was looped as many times as necessary for the participant to be satisfied with their soundscape design. The experiment stopped when the participant was satisfied with their soundscape design. The experimental variables derived from this experiment were: selecting or deselecting each sound source (a binary variable), adjusting the level of each source (a continuous variable), rating whether they expected each source to be present (a binary variable), and rating the pleasantness of each source (a nine-point integer semantic differential scale).

3.2 Results and Discussion

All the participants reported that they enjoyed the experiment, approaching the soundscape design task as a creative activity. Several remarked on the educative aspects. Intuitive controls are probably necessary for this to work; in another experiment, participants were asked to vary the position of each source using three controls at once and they all found this too difficult.

Figure 5 shows that there is a clear relationship between whether a sound was expected and whether it was selected for the user's soundscape design. Both expectation and inclusion are binary variables, so the values shown in Fig. 5 are mean values from the subject group. The extreme ends of the scale therefore represent agreement across the group to include or exclude. The sounds in the middle produced individual differences between participants. For example, everyone included footsteps and all but one person excluded the string quartet. But half the group included the crane and half excluded it. Informal verbal responses from the participants suggest that the meaning of the source may play a significant role in sound selection. (For example, the string quartet playing Pachelbel's Canon was felt to be associated with Christmas, while the experiment was conducted in Spring.)

Figure 6 shows that there is a bi-modal distribution of pleasantness, with no strong relationship to inclusion. As several other studies have found, participants dislike mechanical and transport sounds and like human and natural sounds. The graph seems to show that participants include or exclude a sound independently of whether they find it pleasant or not. This suggests that they designed the soundscape based on what was expected or appropriate rather than on simply what they liked.

Figure 7 shows that there is also no clear relationship between pleasantness and the level set by the participants. Again, this independence indicates that participants did not use pleasantness in the soundscape design. There is, however, a large spread of levels, indicating that the 'mix' of the soundscape varied considerably between participants. When given the opportunity, participants will produce an individual soundscape. This is perhaps analogous to individual preference in positioning oneself in a real environment in order to influence the relative level of each sound. Figure 7 also shows that participants have tended to set the level of each sound below the recorded level (at a mean of -12.3

dB over all settings). This is perhaps because they were conducting the experiment in the very quiet setting of a semi-anechoic chamber.

4 Conclusion

The attempt to replicate a soundscape dimensional experiment has been successful. Using similar semantic differential scales in different soundscape locations has resulted in similar psychological spaces. The dimensions found in the reproduction are similar to those in the field, and the four different soundscapes reproduced have similar dimensions. It is suggested that the weight of evidence in the literature is now sufficient for the first two dimensions of calmness/pleasantness and activity/eventfulness to be regarded as a ‘standard model’ for the perceptual dimensions of soundscapes. The main effect of conducting a soundscape listening experiment with laboratory ambisonic reproduction seems to be to increase the variance explained (that is, to reduce the error). We therefore conclude that this form of reproduction is ecologically valid for dimensional as well as semantic aspects of the soundscape experience.

Ambisonic reproduction can also be used as the basis for a simple soundscape synthesis with an ambient background and foreground sounds mapped as point sources in the reproduction. This allows real-time continuous manipulation of the soundscape and participants were able to use this system to design a soundscape that expressed their intentions. It was found that the designed soundscapes seemed to be based more on participant expectation than on their preference for individual sounds. The success of this simple synthesis suggests that further research into more accurate simulation of complex acoustic environments might eventually lead to a system for auralising and designing the soundscape of locations while they are still on the drawing board.

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Table 1. Semantic differential scales used in the experiment.

Comfort	5	4	3	2	1	0	1	2	3	4	5	Discomfort
Quiet-Noisy												Calming-Agitating
Pleasant-Unpleasant												Smooth-Rough
Natural-Artificial												Hard-Soft
Like-Dislike												Fast-Slow
Gentle-Harsh												Sharp-Flat
Boring-Interesting												Varied-Simple
Social-Unsocial												Reverberant-Anechoic
Communal-Private												Far-Near
Meaningful-Insignificant												Directional-Universal

Table 2. PCA Pattern matrix showing how each semantic scale loads onto the four dimensions from all soundscapes combined (the rotation method was Oblimin with Kaiser normalisation).

	Component			
	1	2	3	4
Variance explained (%)	41	10	7	7
Comfort-Discomfort	0.892	0.009	0.058	-0.067
Quiet-Noisy	0.866	0.029	-0.028	0.04
Pleasant-Unpleasant	0.865	0.095	0.021	-0.081
Natural-Artificial	0.384	0.046	0.527	0.267
Like-Dislike	0.905	0.205	-0.035	-0.002
Gentle-Harsh	0.931	-0.065	0.031	-0.044
Boring-Interesting	-0.541	-0.452	0.1	0.09
Social-Unsocial	0.379	0.018	0.724	-0.002
Communal-Private	-0.238	0.042	0.778	-0.063
Meaningful-Insignificant	0.513	0.588	0.09	0.066
Calming-Agitating	0.915	-0.012	-0.014	-0.133
Smooth-Rough	0.835	-0.146	0.06	0.187
Hard-Soft	-0.757	0.266	-0.041	0.129
Fast-Slow	-0.693	0.512	-0.038	-0.017
Sharp-Flat	-0.082	0.528	0.007	0.506
Varied-Simple	-0.324	0.609	0.274	-0.142
Reverberant-Anechoic	-0.003	0.001	-0.106	-0.375
Far-Near	0.062	0.326	-0.082	-0.473
Directional-Universal	-0.085	0.073	-0.322	0.747

Table 3. Foreground sounds recorded for the soundscape synthesis.

Call	Newspaper ('Big Issue') seller calling
Clock	Chimes of St Ann's church clock
Cleaner	Mechanical street cleaning machine
Steps	Footsteps
Rubbish	Bin lorry loading rubbish
Car	Passing car, on cobbled road
Birds	Mixed birdsong
Crossing	Pedestrian crossing beeping
Quartet	String quartet playing Pachelbel's Canon
Fountain	Medium-sized Fountain
Compressor	Air compressor for construction sites
Crane	Moving construction crane
Speech	English speech babble
French	Conversation in French
Busker	Busker strumming an acoustic guitar
Sprinkler	Sprinkler watering grass

Figure titles

Figure 1. Snapshots of the four locations; (a) St Ann's Square (A); (b) St Ann's Square (B); (c) Pedestrian underpass; (d) Busy road.

Figure 2. Mean scale values for the four soundscapes; (a) St Ann's Sq (A) (-) and Busy road (...); (b) St Ann's Sq (B) (-) and Pedestrian underpass (...). Negative values on the scale are associated with the first word in the semantic pair, and positive values with the second word.

Figure 3. Semantic scales plotted as vectors on the first three principal components for each location. Vectors associated with component 1 are in red, those with component 2 in cyan and those with component 3 in green.

Figure 4. Semantic scales plotted as vectors on the first three principal components for all locations combined. Vectors associated with component 1 are in red, those with component 2 in cyan and those with component 3 in green.

Figure 5. Each foreground sound in the synthesised soundscape could be included or excluded, and was also rated as expected or not by the participants. Expectation is plotted against inclusion ($r=0.86$).

Figure 6. Foreground sound pleasantness rating against inclusion in the synthesised soundscape. The error bars show standard error.

Figure 7. Pleasantness rating against the level of the sound set by participants. The level is expressed relative to the actual level recorded in the field.

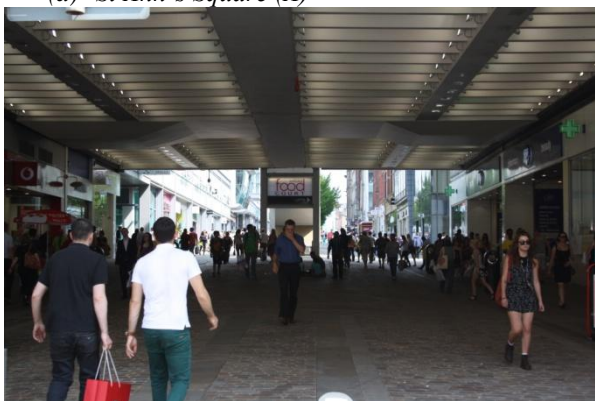
Figure 1



(a) *St Ann's Square (A)*



(b) *St Ann's Square (B)*



(c) *Pedestrian underpass*



(d) *Busy road*

Figure 2

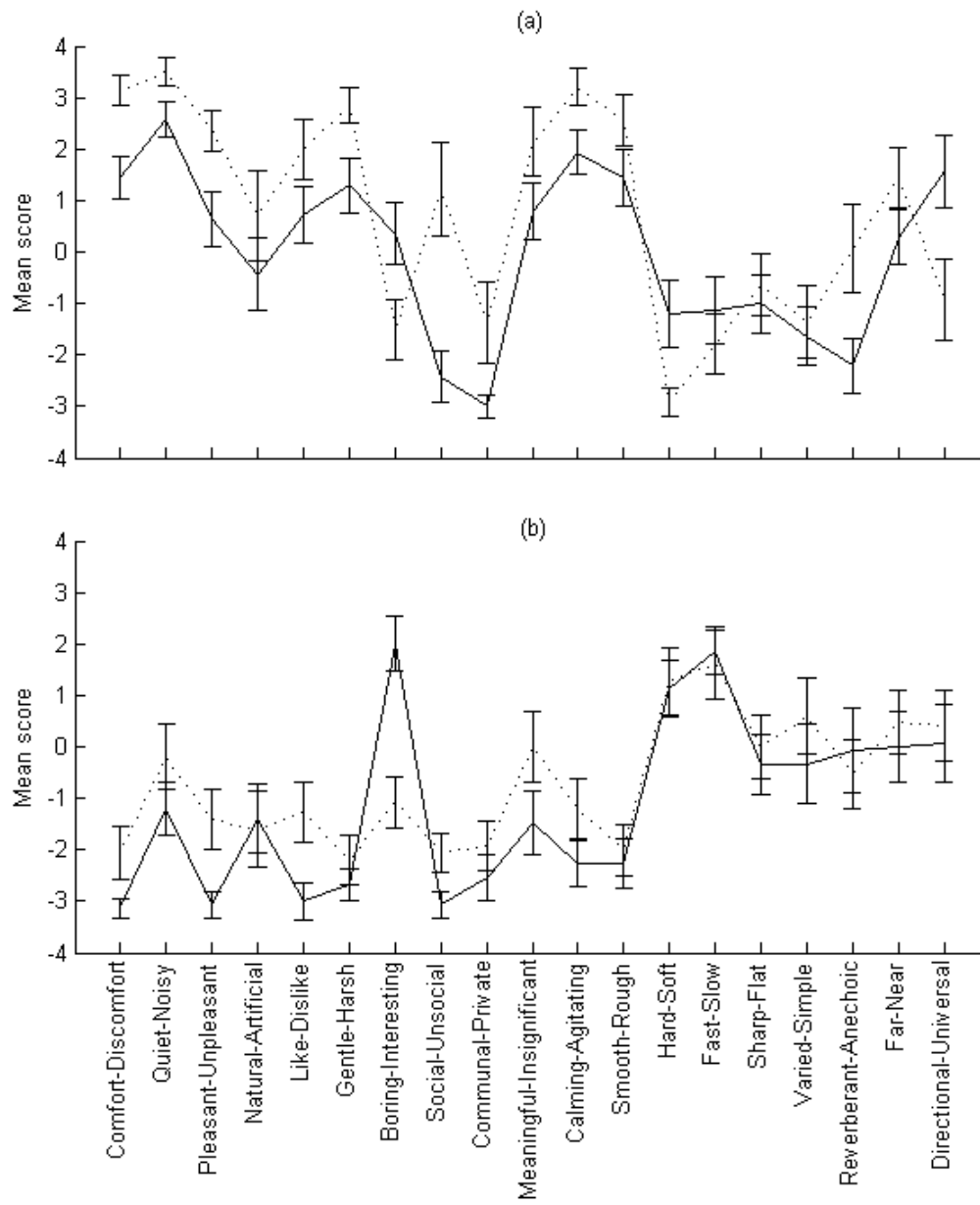


Figure 3.

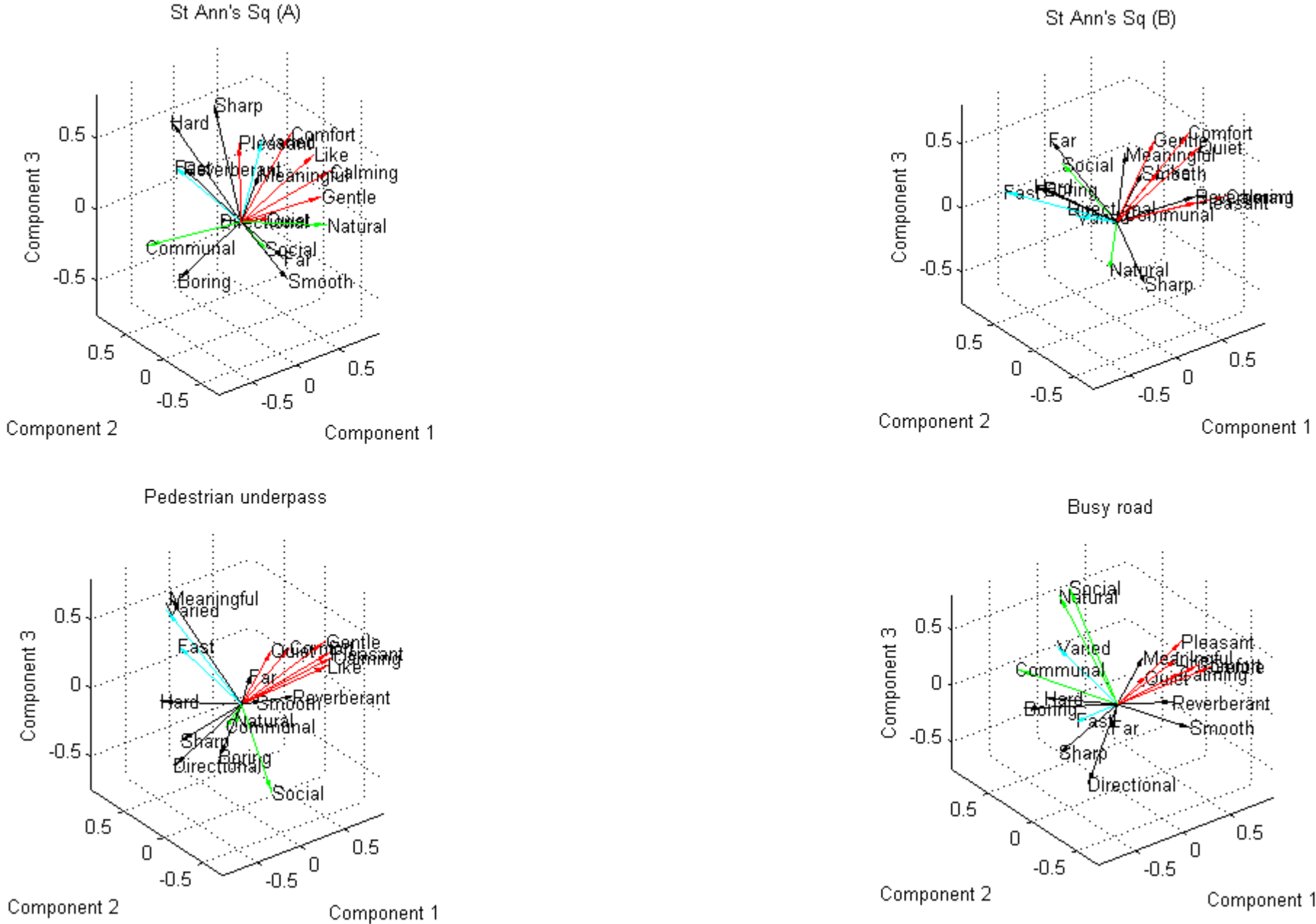


Figure 4.

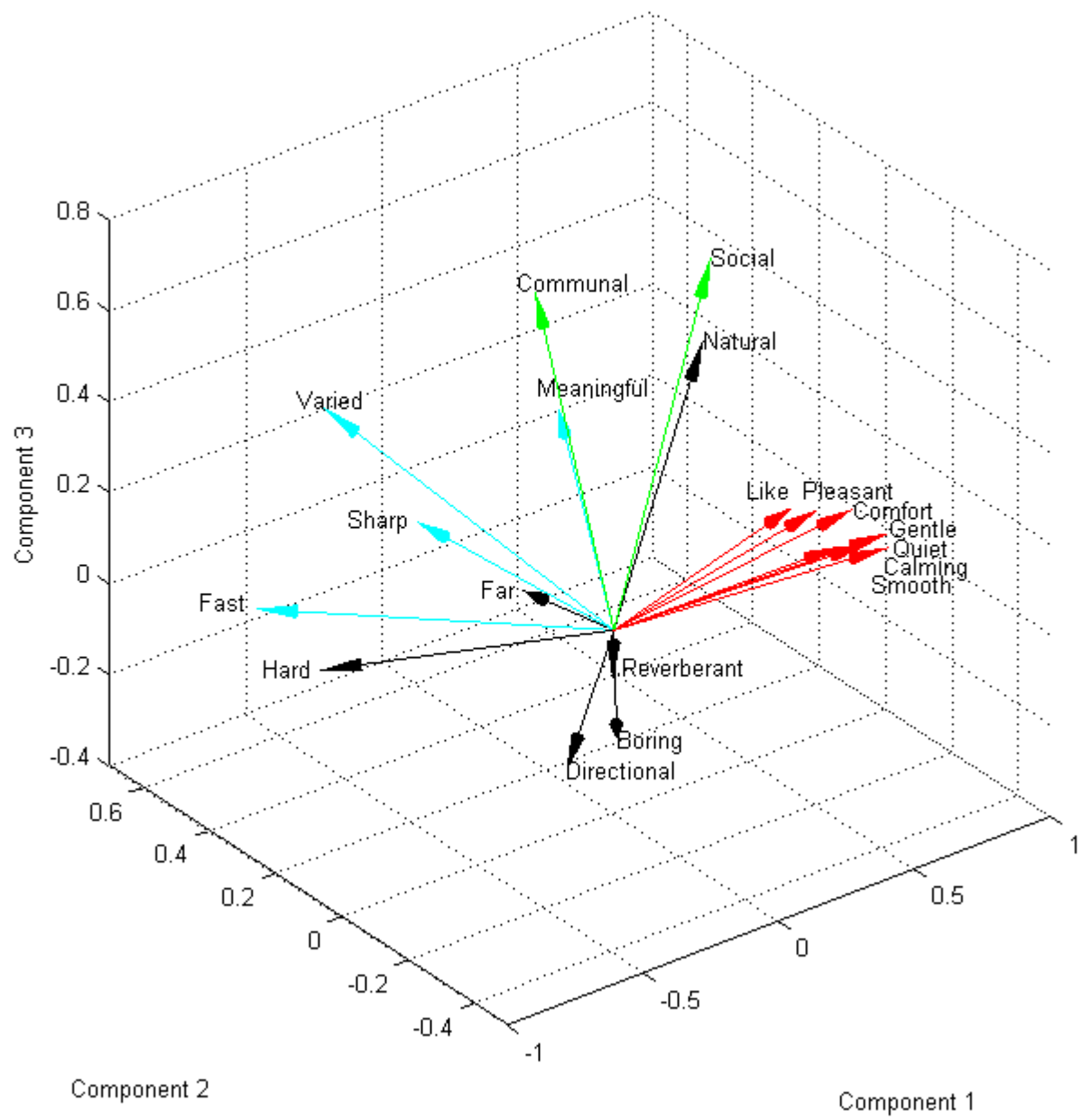


Figure 5.

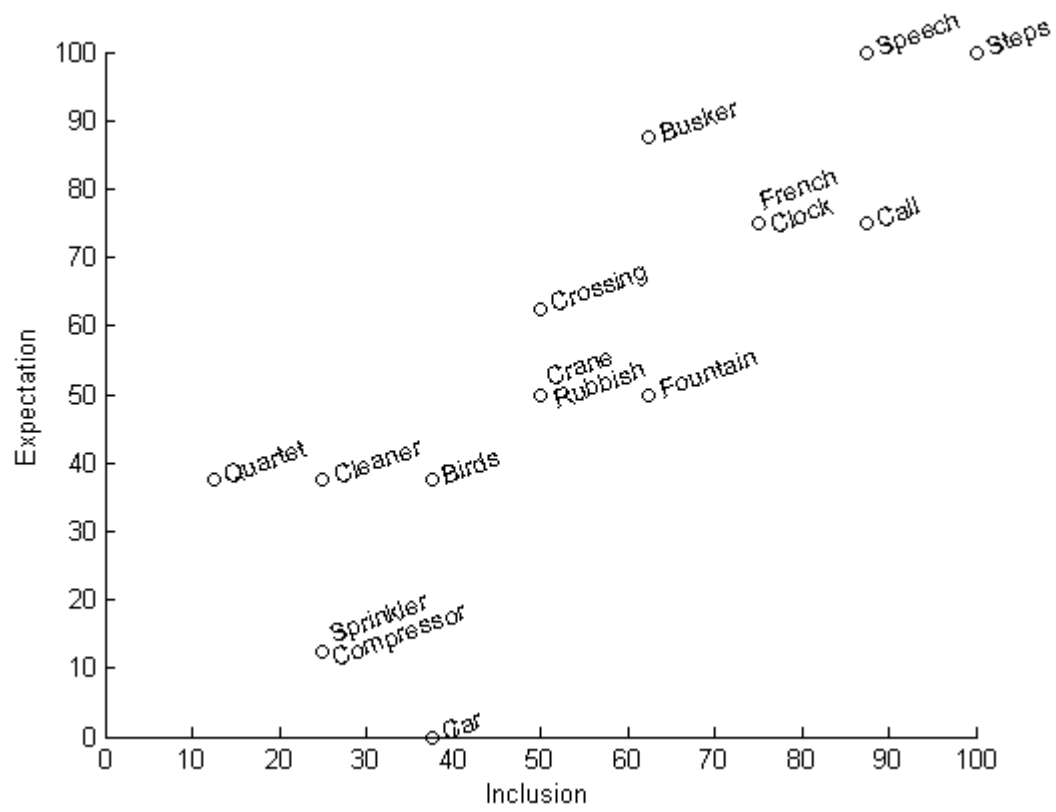


Figure 6.

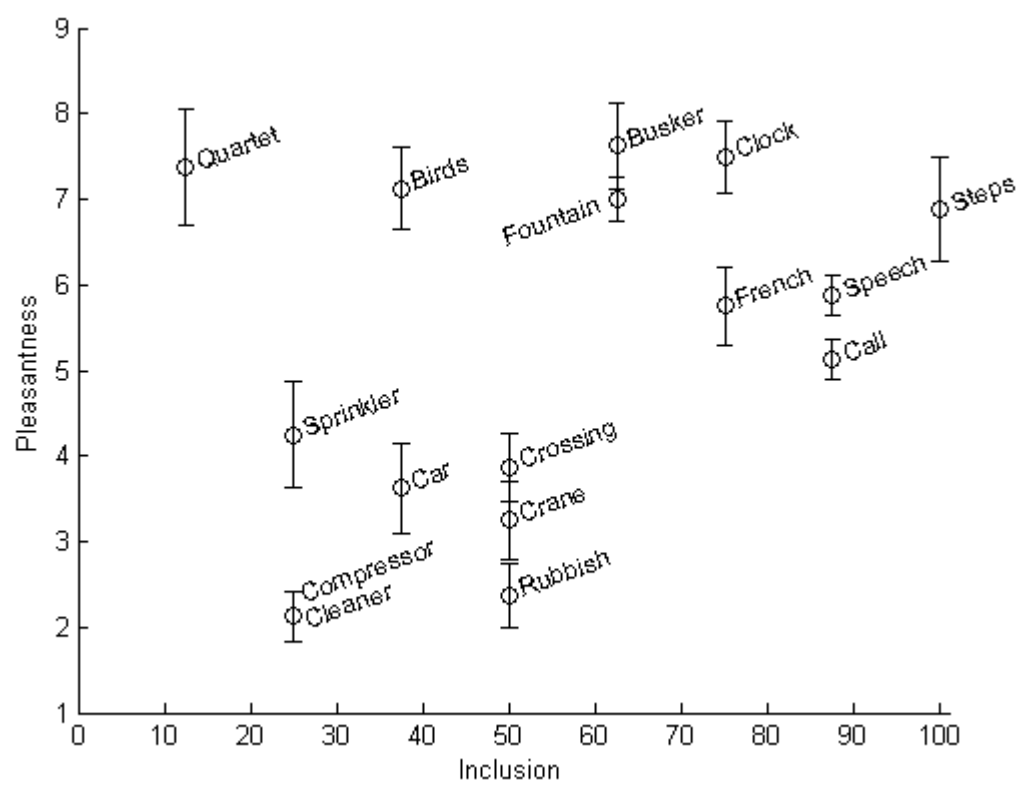


Figure 7.

